

Characteristics of Parton Energy Loss Studied with High- p_T Particle Spectra from PHENIX

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Abstract. In the first three years of the physics program at the Relativistic Heavy Ion Collider (RHIC) a picture was established in which the suppression of hadrons at high transverse momenta (p_T) in central Au+Au collisions is explained by energy loss of quark and gluon jets in a medium of high color-charge density. Measurements of single particle spectra for a smaller nucleus (Cu), for different center-of-mass energies and with higher statistics were performed in the subsequent years and are used to test predictions and assumptions of jet quenching models in more detail. The measurements presented here are consistent with a parton energy loss scenario so that these models can be used to relate the observed suppression to properties of the created medium.

1. Introduction

The study of p+p, d+Au, and Au+Au collisions in the first three years at RHIC showed that (i) hadrons at high p_T ($p_T \gtrsim 6 \text{ GeV}/c$) produced in central Au+Au collisions are strongly suppressed, (ii) direct photons in Au+Au collisions at high p_T are not suppressed, and (iii) high- p_T hadrons in d+Au are not suppressed [1]. The particle production in collisions of two heavy-ion species A+B with respect to p+p collisions was quantified with the nuclear modification factor $R_{AB} = (dN/dp_T|_{A+B})/(\langle T_{AB} \rangle \times d\sigma/dp_T|_{p+p})$ where the nuclear overlap function T_{AB} is related to the number of independent nucleon-nucleon collisions according to $\langle T_{AB} \rangle = \langle N_{\text{coll}} \rangle / \sigma_{\text{inel}}^{\text{NN}}$.

These observations provided strong evidence for jet quenching: quarks and gluons lose energy in a medium of high color-charge density created in Au+Au collisions whereas direct photons leave the medium unscathed and follow the scaling with $\langle T_{AB} \rangle$ since they interact only electro-magnetically. With high- p_T single particle spectra measured after the initial three runs at RHIC assumptions and predictions of parton energy loss models can be studied in more detail. In particular, the centrality and p_T dependence of hadron and direct-photon production can be tested at higher p_T . Moreover, the new data allow to test the dependence of the hadron suppression on the heavy-ion species (Cu instead of Au), on the hadron species, and on $\sqrt{s_{\text{NN}}}$.

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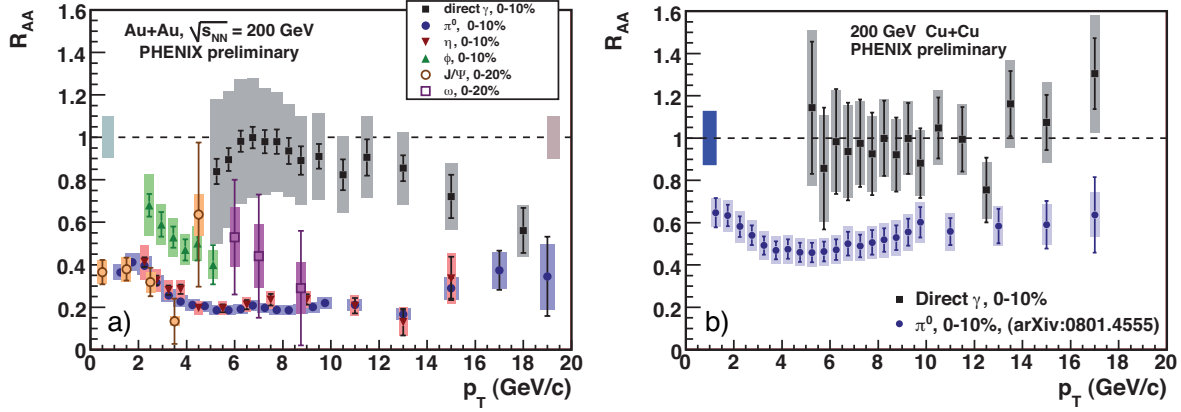


Figure 1. a) R_{AA} in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for direct photons and various mesons (π^0 , η , ϕ , J/Ψ , ω). b) R_{AA} in central Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV for direct photons and π^0 's.

2. Results

Neutral-pion spectra in p+p and central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, measured up to $p_T \approx 13$ GeV/c in the second physics run at RHIC, are now available up to $p_T \approx 20$ GeV/c. Fig. 1a shows that the observed suppression remains approximately constant at $R_{AA} \approx 0.2$ up to highest p_T [2]. Direct-photon yields in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, now available up to $p_T \approx 18$ GeV/c, do not appear to scale with T_{AB} at the highest p_T ($R_{AA} \approx 0.6$). Possible explanations of this observation include the difference between the parton distributions in protons and neutrons (isospin effect), the modification of the parton distributions in nuclei (EMC effect), and the suppression of direct photons which result from the fragmentation of partons. Interestingly, a suppression of direct-photon production at $p_T \approx 17$ GeV/c is not observed in central Cu+Cu collisions at the same energy (Fig. 1b).

The R_{AA} for different mesons in Fig. 1a shows that not all mesons are suppressed by the same factor. Neutral pions and η 's exhibit the same suppression which is consistent with a picture in which these particles are produced in the fragmentation of partons outside the hot and dense medium. The amount of suppression for J/Ψ 's at mid-rapidity is similar to that of π^0 's and η 's. However, ω and ϕ mesons appear to be less suppressed. This interesting pattern provides an important test for jet quenching models.

The comparison of the π^0 suppression in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}$ unveils a simple scaling: The suppression only depends on the number of participating nucleons (N_{part}) for the same $\sqrt{s_{NN}}$ as shown in Fig. 2a. Such a scaling with N_{part} is consistent with a parton energy loss picture [7]. Fitting the centrality dependence of R_{AA} in central Au+Au collisions for $p_T > 10$ GeV/c with the function $R_{AA} = (1 - \kappa N_{part}^\alpha)^{n-2}$ yields $\alpha = 0.56 \pm 0.10$, consistent with $\alpha \approx 2/3$ expected in parton energy loss scenarios [2, 7].

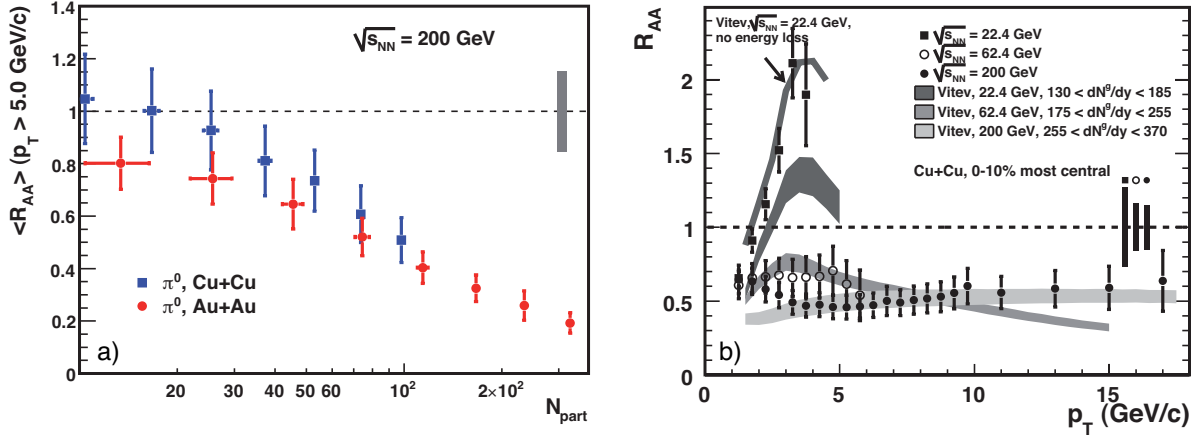


Figure 2. a) Centrality dependence of the π^0 R_{AA} in Cu+Cu and Au+Au at $\sqrt{s_{NN}} = 200$ GeV. b) Energy dependence of the π^0 R_{AA} in central Cu+Cu collisions. The shaded bands represent parton energy loss calculations [3].

The $\sqrt{s_{NN}}$ dependence of the π^0 suppression provides further constraints for parton energy loss models. A comparison of the π^0 production in central Au+Au collisions at 62.4 and 200 GeV shows that for $p_T \gtrsim 6$ GeV/c the R_{AA} at 62.4 GeV approaches the R_{AA} at 200 GeV [4]. This suggests that the smaller parton energy loss at 62.4 GeV is offset by the steeper parton p_T spectrum at this energy. The measurement of R_{AA} in Cu+Cu at 22.4, 62.4, and 200 GeV (Fig. 2b) indicates that parton energy loss starts to dominate over Cronin enhancement between 22.4 GeV and 62.4 GeV [3]. The π^0 suppression at 62.4 and 200 GeV is consistent with a parton energy loss calculation in which the initial gluon density is derived from measured charged particle multiplicities [7]. The enhancement at 22.4 GeV is consistent with a scenario without parton energy loss.

Characterizing the parton energy loss ΔE with R_{AA} is problematic since R_{AA} not only depends on ΔE but also on the steepness of the parton p_T spectrum. The parton p_T spectra become steeper with decreasing $\sqrt{s_{NN}}$ leading to a smaller R_{AA} for the same ΔE . This might explain why a significant π^0 suppression ($R_{AA} \approx 0.5 - 0.6$) is even observed at $\sqrt{s_{NN}} = 17.3$ GeV in very central Pb+Pb collisions [5]. For a power law spectrum $1/p_T dN/dp_T \propto p_T^{-n}$ and an approximately constant R_{AA} the fractional parton energy $S_{loss} = \Delta p_T/p_T$ loss can be estimated as $S_{loss} = 1 - R_{AA}^{1/(n-2)}$ where n is obtained from a power law fit of the p+p spectrum [6] at the same energy. At $\sqrt{s_{NN}} = 17.3, 62.4, 130$ and 200 GeV the values 11.4, 9.2, 8.2, 8.2, respectively, were used for the power n . For the CERN SPS energy of 17.3 GeV a π^0 spectrum measured in p+C collisions was used as a replacement for a p+p spectrum [5]. As a function of $\sqrt{s_{NN}}$ S_{loss} appears to increase smoothly with $\sqrt{s_{NN}}$ in central collisions with $N_{part} \gtrsim 320$ and reaches ~ 0.2 at the top RHIC energy of $\sqrt{s_{NN}} = 200$ GeV (Fig. 3a).

In order to constrain medium properties with the aid of parton energy loss models a fitting procedure was described in [8] that takes different kinds of systematic uncertainties (point-by-point uncorrelated, point-by-point correlated, and overall

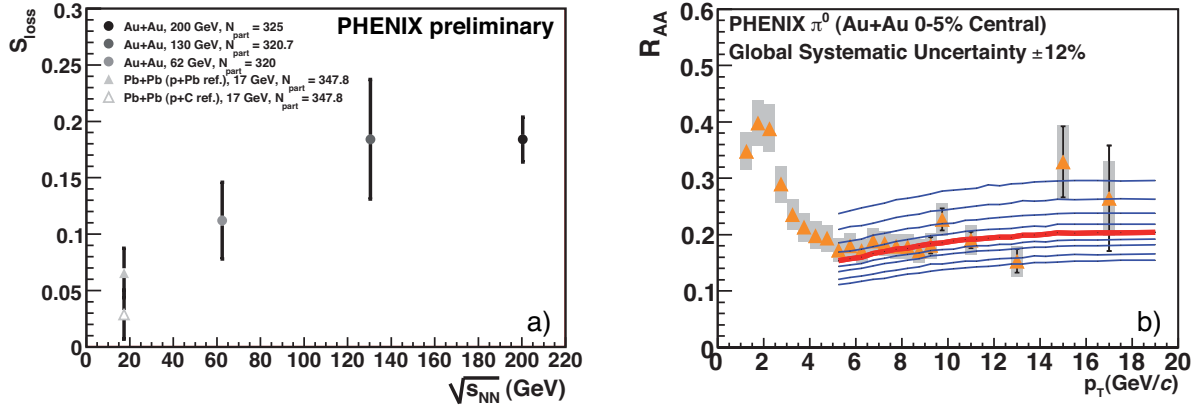


Figure 3. a) Energy dependence of S_{loss} for central Au+Au (RHIC) and Pb+Pb (CERN SPS) collisions as determined from the average R_{AA} in the range $2.5 \lesssim p_T \lesssim 3.5$ GeV/c. b) Parton energy loss calculation [9] for various values of the initial energy density ε_0 compared to the measured $\pi^0 R_{\text{AA}}$ at $\sqrt{s_{\text{NN}}} = 200$ GeV.

normalization uncertainties) into account. As an example, results of the calculation described in [9] are shown in Fig. 3b for different values of the energy loss parameter ε_0 . The optimal fit (thick line) corresponds to $\varepsilon_0 = 1.9^{+0.2}_{-0.5}$ GeV/fm (one standard deviation). In general, for the models described in [8] medium parameters are constrained within 20 – 25 % at the 1σ level. However, it needs to be stressed that at this stage the theoretical uncertainties in the models are much larger so that, *e.g.*, the values obtained for the medium parameter \hat{q} can differ by an order of magnitude.

3. Conclusions

The flat $R_{\text{AA}}(p_T)$ up to $p_T \approx 20$ GeV/c and the centrality dependence in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV, the scaling of R_{AA} with N_{part} in Cu+Cu and Au+Au for the same $\sqrt{s_{\text{NN}}}$, the identical suppression for π^0 's and η 's, and the energy dependence of the π^0 production in Cu+Cu are observations which are all consistent with a parton energy loss picture. More work, however, is needed to understand the different suppression patterns of ϕ and ω mesons as compared to pions and η 's and the scaling of direct photons at high p_T in central Cu+Cu and Au+Au collisions.

References

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